Review/Survey Research

A Review of Quality of Service (QoS) Route Provisioning in Mobile Ad Hoc Networks

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ABSTRACT: *With the increase of portable devices as well as rapid advancement in computing and wireless technologies, mobile ad hoc networking is gaining importance with the increasing number of widespread applications. Quality of service (QoS) routing plays a prominent role for providing QoS in mobile wireless ad hoc networks. Real time and multimedia applications need stringent QoS requirements. Providing a complete quality-of-service (QoS) solution for the ad hoc networking environment requires the interaction and co-operation of several components which include a QoS routing protocol, a resource reservation mechanism and a QoS capable medium access control (MAC) layer. The tasks of QoS routing are in general selecting routes with satisfied QoS requirement(s), and achieving global efficiency in terms of resource utilization. QoS is more difficult to guarantee in mobile ad hoc networks than in other type of networks due to the sharing of wireless bandwidth among adjacent nodes, its dynamic topology and generally imprecise network state information. This work is intended to provide a broad and comprehensive review of the QoS routing protocols proposed for ad hoc networks. This paper also describes important QoS frameworks for MANETs which attempt to provide required/promised services to each user or application.*

Categories and Subject Descriptors
C.2.1[Network Architecture and Design**];**Network Topology: **C2.4 [**Distributed Systems**];**Client/Server

General Terms
Mobile networks, Wireless Technology

Keywords: Mobile ad hoc networks (MANETs), Quality-of-service (QoS), QoS routing, QoS framework, Code division multiple access (CDMA), Time division multiple access (TDMA), MAC, Multi-path routing

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1. Introduction

A Mobile ad hoc network (MANET) [1,16] is a dynamic multi-hop wireless network that is established by a group of mobile nodes on a shared wireless channel without the use of any pre-existing network infrastructure or centralized administration. Ad hoc mobile wireless networks (Figure 1) are self-creating, self-organizing and self-administering. They can be created and used any where and any time. Their topology is dynamic, decentralized, ever changing and the nodes may move around arbitrarily. The classic applications of mobile wireless ad hoc networks include supporting battlefield communications, disaster recovery (earthquake, fire), law enforcement, public meeting, virtual class room, collaborative computing etc. The ad hoc networking technology has stimulated substantial research activities in the past ten years. Routing protocols in MANET are generally categorized as proactive (table driven), reactive (on demand) and hybrid protocols. Proactive routing protocols have lower latency and higher overhead whereas on-demand routing protocols have higher latency and lower overhead. Much work has been done on routing in ad hoc networks, but most of them focus only on best-effort data traffic. Recently, because of the rising popularity of multimedia applications and potential commercial usage of MANETs, QoS support in ad hoc networks has become a topic of great interest. Traditional Quality of Service (QoS) routing protocols developed for wired networks can not be easily adapted to ad hoc networks due to dynamic topology of these networks and error-prone nature of wireless links. To support QoS, the link state information such as bandwidth, delay, jitter, cost, loss rate and error rate in the ad hoc network should be available and manageable. However getting and managing the link state information in a MANET is non trivial because the quality of a wireless link changes with the surrounding circumstance. Furthermore, the resource limitations and the mobility of hosts add to this complexity.

The rest of the paper is organized as follows. In section 2, we first introduce QoS and different QoS metrics used by routing protocols. The issues and challenges involved in providing QoS routing in mobile ad hoc networks are identified in section 3. In section 4, we describe different QoS frameworks proposed for ad hoc networks which use an inter-layer approach to offer desired QoS services. Different design approaches in addition to merits and demerits of a wide range of routing protocols (operating at network layer as well as network layer and MAC layer) subject to single as well as multi-QoS constraints especially bandwidth, end-to-end delay, reliability, battery life and routing load proposed in the literature are taken up at a length in section 5. These QoS routing protocols are classified according to which best effort routing protocol (DSDV, AODV, DSR, and TORA) [64] they extend or to which they are closest in design. Section 6 gives a summary of QoS routing protocols classification in Table 1. Finally, section 7 concludes with the open research problems in the active field of QoS routing, which need in depth investigation.

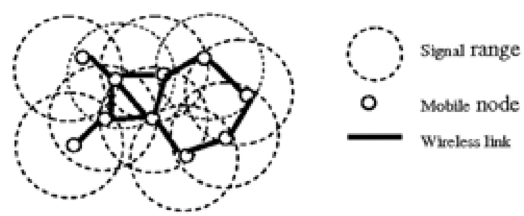

Figure 1. A Mobile Ad Hoc Network.

2. Quality of Service Metrics

As defined in [2, 3,33] Quality-of-Service is "*a set of service requirements to be met by the network while transporting a flow*". Here a flow is a packet stream from source to destination with an associated Quality of Service. According to CCITT, QoS is "*the collective effect of service performance which determines the degree of satisfaction of a user of a service*". A service can be characterized by a set of measurable pre-specified service requirements such as minimum bandwidth, maximum delay, maximum delay variance (jitter), and maximum packet loss rate, hop count, and path reliability. A number of QoS parameters can be measured and monitored to determine whether a service level offered or received is being achieved. Different services require different QoS parameters. For multimedia applications bandwidth, delay and delay jitter while for emergency services, network availability and for group communication battery life are prime concerns. Generally QoS parameters that are important are bandwidth, delay, jitter, battery life, processing power, buffer space, reliability, hop count, probability of packet loss, availability etc. Power consumption is another QoS attribute which is more specific to mobile ad hoc network. Although multiple metrics can certainly model both networks and applications more accurately, the problem is that finding a path subject to multiple metrics is inherently difficult and in many cases is considered NP-complete. Metrics are used in QoS routing as a form of measure so that we can keep track of the values we need to calculate the best route on the requirements of the QoS. Metrics may depend on single or multiple parameters. Quality of Service metrics can be broadly classified into three groups namely additive, multiplicative and concave. Let G= (V, E) be the network with $|V|$=n nodes and $|E|$=m arcs and met_{ij} a metric for link (i,j). The value of a metric over any directed path p= (i,j,k,…,q,r) can be one of the following compositions [4,5]:

Additive metrics: Metric *met* is additive if

$$met(p) = met_{ij} + met_{jk} + \ldots + met_{qr}.$$

Examples of such metrics are delay, jitter, hop-count and cost. They follow the additive composition rule.

Multiplicative metrics: Metric *met* is multiplicative if

$$met(p) = met_{ij} \times met_{jk} \times \ldots \times met_{qr}.$$

The probability of successful transmission (pst) follows the multiplicative composition rule. The composition rule for loss probability (L_p) is more complicated.

$$met(p) = 1 - ((1 - met_{ij})) \times (1 - met_{jk}) \times \ldots \times (1 - met_{qr})).$$

It can be transformed to an equivalent metric pst.

Concave/Convex metrics: Metric *met is* concave/convex if the overall metric of a route is the minimum or maximum of all the metrics over the individual links along the path.

$$met(p) = \min\{met_{ij}, met_{jk} \ldots met_{qr}\} \quad \text{or}$$

$$met(p) = \max\{met_{ij}, met_{jk} \ldots met_{qr}\}.$$

Bandwidth follows the concave composition rule.

3. QoS Route Provisioning in Ad Hoc Wireless Networks: Issues and Challenges

Due to the broadcast and dynamic nature of MANETs, providing different quality of service levels rather than best effort in a constantly changing environment is a challenging task. The inherent stochastic feature of communications quality in ad hoc network makes it difficult to offer fixed guarantees on the services offered to a user. An adaptive QoS must be implemented over the traditional resource reservation to support the multimedia services. This section describes QoS route provisioning challenges [6,7,8,69] in MANETs and discusses the problems in applying common mechanisms used in wired networks to mobile ad hoc networks.

Dynamic Topology: *As* the nodes are mobile, the network topology may change rapidly and unpredictably and the connectivity among the nodes may vary with time. Therefore ad hoc networks should adapt to the traffic, propagation conditions as well as the mobility patterns of mobile nodes. Topology change unpredictably results in broken links and stale routes. As the topology frequently changes, managing the link state information to support QoS (such as delay, bandwidth, cost, loss rate, and error rate) in the network is very difficult.

Power-aware routing: Limited power supply in handheld devices can seriously inhibit packet forwarding in ad hoc mobile environment. Hence techniques that take into account each node's power metrics and try to minimize power consumption are more desirable and provide a way to create more long-lived routes.

Admission Control: In order to provide acceptable QoS on each connection on a network with limited resources, it may be necessary to deny some requests for connections. By managing admission onto the network in this way, the levels of QoS guaranteed to the users already on the network will be able to be maintained.

Imprecision in state information: The nodes in an ad hoc wireless mobile network often have to maintain both the link-specific (bandwidth, delay, delay jitter, loss rate, error rate, stability, and cost) as well as flow-specific state information (session ID, source address, destination address, and QoS requirements of the flow e.g. minimum bandwidth requirement, maximum delay, and maximum delay jitter) for routing. Often the state information is inherently imprecise due to dynamic network topology and channel characteristics. Hence routing decisions may not be accurate, resulting in some of the real-time packets missing their deadlines.

Lack of central co-ordination: Unlike wireless LANs and cellular networks, Ad hoc Wireless Networks do not have central controllers to coordinate the activity of nodes. This further complicates QoS provisioning in Ad hoc wireless networks.

Unreliable shared radio channel: The radio channel is a broadcast medium by nature so during propagation through the wireless medium, the radio waves suffer from several impairments such as attenuation, multi-path propagation, and interference from other wireless mobile devices. Due to fading and outside interference, the wireless channel has a high packet loss rate.

Hidden and exposed terminal problems: In a MAC layer with the traditional carrier sense multiple access (CSMA) protocol, multi-hop packet relaying introduces the hidden terminal problem and exposed terminal problems.

Resource limitations: In MANETs resources such as bandwidth, battery life, storage space, and processing capability are limited and scarce. Out of these, bandwidth and battery life are very critical. Their availability significantly affects the performance of the QoS provisioning mechanism. Hence efficient resource management mechanisms are required for optimal utilization of these scarce resources. All the techniques for QoS provisioning should be power-aware and power efficient.

Security: In addition to the common vulnerabilities of wireless connection, an ad hoc network has its particular security problems. The feature of distributed operation requires different schemes of authentication and key management. Due to communication in free space, Ad hoc wireless links are susceptible to various kinds of attacks ranging from passive eavesdropping to active impersonation, message replay and message distortion. Active attacks might allow the adversary to delete messages, inject erroneous messages, modify messages and impersonate a node, thereby violating availability, integrity, authentication and nonrepudiation.

Scalability: Scalability in ad hoc mobile wireless networks presents more complex problems than in wired networks due to random movement of nodes and the bandwidth and power limitations. The protocol scalability is expressed as the efficient support of large number of users, links, nodes, simultaneous sessions etc.

Reliability: Reliable services are very important in some applications such as military battlefields and emergency operations that are supported by mobile ad hoc wireless networks. Offering reliable delivery of data to a group of fast moving nodes that change their position continuously adds substantial complexity to the already complicated problem of efficient communication in ad hoc networks.

4. QoS Framework

Quality of service provisioning in ad hoc network is not dedicated to any specific layer rather it requires coordinated efforts from all layers. Thus QoS support components include: QoS model, QoS routing, QoS signaling, QoS adaptation and QoS medium access control (MAC). A framework [26,78] for QoS is a complete system that attempts to provide required/promised services to each user or application.

4.1 Components of a QoS Framework

Various components of a QoS framework is depicted in Figure 2. We briefly describe these components here.

QoS Model: It is a key component of any QoS framework and defines the way user requirements are to be fulfilled. Here the key design issue is whether to serve users on a per session basis or on a per class basis. It is the system goal that has to be implemented. All other QoS components, such as QoS signaling, QoS Routing and QoS MAC must cooperate together to achieve this goal.

QoS Routing: It is basically part of the network layer and searches to find all or some of the feasible paths in the network having enough resources that can satisfy QoS objectives under given resource constraints. A QoS routing protocol should work together with QoS signaling to establish paths through the network that meet end-to-end QoS requirements such as delay, bandwidth, or multi-metric constraints. QoS routing also performs the task of route maintenance to prevent sudden drop in the performance when there is a decrease in the ability of the path to accommodate QoS of the given flow.

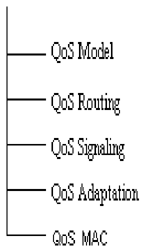

Figure 2. Components of QoS Framework

QoS Signaling: It operates above network layer. It acts as a control center in providing QoS support. It is responsible for flow admission control as well as resource reservation [79] along the established route. QoS signaling systems can be in-band signaling or out-of-band signaling. In in-band signaling, control information is piggybacked within data packets while in out-of-band signaling control information is sent as explicit packets.

QoS Adaptation: The purpose of QoS adaptation is to hide all the environment-related features from awareness of the multimedia-application above and provides an interface for applications to interact with QoS control.

QoS MAC: QoS MAC protocol solves the problems of medium contention, hidden and exposed terminal problem, supports reliable unicast communications, and provides resource reservation for real time traffic in a distributed wireless environment. Among numerous MAC protocols [75] and improvements that have been proposed, one protocol that can provide QoS guarantees to real time traffic in a distributed wireless environment is Black-Burst (BB) [36].

4.2 QoS Frameworks for Wired Networks

Before considering QoS in MANETs, it will be instructive to have a brief look at QoS provisioning in wired networks. There are two service models already proposed by the IETF. These are Integrated Services (IntServ) model [74] and Differentiated Services (DiffServ) model [50].

4.2.1 IntServ IP QoS Model

IntServ architecture allows sources to communicate their QoS requirements to routers and destinations on the data path by means of a signaling protocol (RSVP) [51]. Hence, IntServ provides per-flow end-to-end QoS guarantees. This model is not appropriate for mobile ad hoc networks as the amount of state information increases in proportion to the number of flows, which results in scalability problem. However, it can be applied to small sized ad hoc networks.

4.2.2 DiffServ IP QoS Model

DiffServ architecture avoids the problem of scalability by defining a small number of per-hop behaviors (PHBs) at the network edge routers and associating a different DiffServ Code point (DSCP) in the IP header of packets belonging to each class of PHBs. Core routers use DSCP to differentiate between different QoS classes on per hop basis. In this way DiffServ solves the problems of scalability but it does not guarantee services on end-to-end basis. This is a main drawback as end-to-end guarantees are required in mobile ad hoc network. Moreover, DiffServ and IntServ require accurate link state (e.g. available bandwidth, packet loss rate etc) and topology information.
In general, due to unique characteristics of MANETs, above wire-based models are not appropriate for MANETs and can not be directly applied to ad hoc networks.

4.3 QoS Frameworks for Mobile Ad Hoc Networks

In the following, we review existing stateful and stateless QoS frameworks for MANETs.

4.3.1 Flexible QoS Model for Mobile Ad Hoc Networks (FQMM)

FQMM [78,52] is a model specifically designed for mobile ad hoc networks. It defines three types of nodes, an ingress node which sends data, an interior node which forwards data to other nodes and an egress node which is a destination node. FQMM proposes a hybrid provisioning scheme which combines the per-flow granularity of IntServ and per-class granularity of DiffServ. This model provides per flow QoS guarantee for high priority flows while lower priority flows are aggregated into a set of service classes (Figure 3). Classification is made at the source node and QoS provisioning is done at every node along the path. This model overcomes the scalability problem up to some extent by classifying the low priority traffic into service classes. It can be used for small to medium size MANET. FQMM addresses the basic problem faced by QoS frameworks and proposes a generic solution for mobile ad hoc networks that can be a base for a better QoS model. However issues such as allotment of per flow or aggregated service for the given flow, amount of traffic belonging to per flow service, decision upon traffic classification and scheduling or forwarding of the traffic by intermediate nodes still need to be resolved.

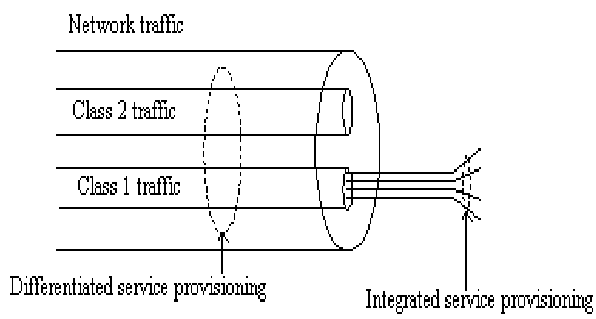

Figure 3. FQMM Model

4.3.2 A QoS Architecture for Real Time Data Transmission in MANET

Lei et al. [46] proposed a QoS architecture that extends from the application layer to the MAC layer for supporting real time data transmission in mobile ad hoc networks as shown in Figure 4.

This QoS architecture includes all networking layers (a QoS transport layer, QoS routing, Queue management and a priority MAC protocol) from the application layer to the MAC layer.

The bold lines indicate the flow of data packets while the thin lines represent control packets flow. The purpose of queue management is to schedule the different priority packets while MAC discriminator is used to differentiate data packets and control packets. Using this architecture, video quality was greatly improved and packet delay was significantly decreased. The performance of multiple different priority streams has not been addressed.

4.3.3 INSIGNIA

INSIGNIA [26] provides a stateful or reservation-oriented lightweight QoS architecture that are specifically designed to deliver adaptive QoS guarantee for real-time traffic. It offers IP based QoS framework for MANETs which is designed to support multimedia traffic and achieve better efficiency in terms of bandwidth and energy consumption through the implementation of inter-layer QoS framework. Control signals are encapsulated into IP data packets with an IP INSIGNIA option (Figure 5) for doing the necessary resource reservation. Like RSVP, the service granularity supported by INSIGNIA is per flow. To establish reservation-based flows between source destination pairs, source nodes initiate fast reservations by setting the appropriate fields in the INSIGNIA IP option field before forwarding packets. Reservation packets traverse intermediate nodes, executing admission control modules, allocating resources and establishing soft-state reservation at all intermediate nodes between source destination pairs. The reservations need to be periodically refreshed by the packets of the flows. In the event of a change in the path resulting from movement of mobile nodes, the first packet along the new path makes fresh reservations along this path thereby doing a fast restoration. Old paths reservations are removed on a timeout.

Flows in the network are assumed to be adaptive to bandwidth availability. INSIGNIA considers two optional QoS levels: base QoS and enhanced QoS. Flow traffic carries MIN/MAX bandwidth requests in the packet headers. At each hop, the flow reserves bandwidth to meet MIN/MAX request. At a bottleneck, a hop where only MIN or best effort QoS can be supported, all the hops preceding the bottleneck will adjust their reservation to no more than the bottleneck's QoS. Finally, base QoS or enhanced QoS traffic will be sent by the sender upon receiving a QoS report from the receiver indicating the total bandwidth reserved along the path.

Even though INSIGNIA presents a quite promising approach to QoS support in mobile ad hoc networks, the system still lacks some basic mechanism. These are mentioned below.

- INSIGNIA has scalability problem due to the flow state information which is kept within the nodes along a path.
- Excess reservation should be avoided or minimized.
- INSIGNIA does not provide any mechanism to dynamically change the frequency by which control signals are inserted into the data packets. This imposes a major processing overhead on the network.
- Since only two bandwidth levels (MAX and MIN) to be used are offered. A more fine grained approach would be needed in order to satisfy application requirements and to fully exploit the resources available.

4.3.4 INORA

INORA [27] is a QoS framework for mobile ad hoc networks that makes use of the INSIGNIA in-band signaling and TORA [64] routing protocol. It represents a cross-signaling approach in a loosely coupled kind of manner. The idea is based on the property of TORA to provide multiple routes between a given source and destination. While INSIGNIA does not take any help from the network with regard to redirecting the flow along routes which are able to provide the required QoS guarantees, INORA gives feedback to the routing protocol on a per-hop basis to direct the flow along the route that is able to satisfy the QoS requirements of the flow. A soft state reservation mechanism is employed for resource reservation. INORA can be classified into two schemes: coarse feedback scheme and class-based fine feedback scheme. INORA is better than INSIGNA in that it can search multiple paths with lesser QoS guarantees. As no resources are reserved before the commencement of actual data and since data packets have to be transmitted as best-effort packets in case of admission control failure at the intermediate nodes, application desiring hard service guarantees may not find suitable this model.

4.3.5 SWAN

Service Differentiation in Stateless Wireless Ad Hoc Networks (SWAN) [53] is a stateless QoS architecture that provides

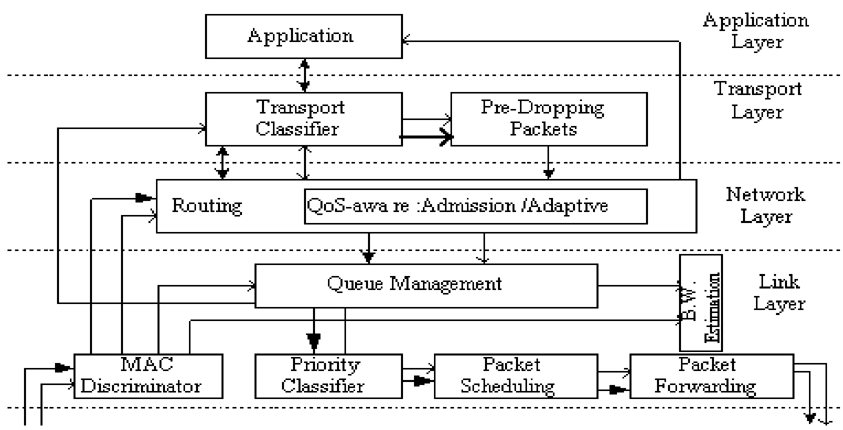

Figure 4. A QoS Architecture for MANET

Service Mode	Payload Type	Bandwidth Indicator	Bandwidth Request	
RES/BE	BQ/EQ	MAX/MIN	MAX	MIN
1 bit	1 bit	1 bit	16 bit	

Figure 5. INSIGNIA IP Option Fields

soft-real time QoS relying on standard best-effort MAC technology (IEEE 802.11) and independent of the employed routing protocol. It avoids additional signaling and complex control mechanisms. In this model intermediate nodes are relieved from the responsibility of maintaining per flow or aggregate state information unlike stateful QoS models such as INSIGNIA and INORA. Data packets are passed through a classifier that distinguishes between real-time (high priority) and best effort (low priority) traffic. It uses rate control for low priority traffic and employs admission control for high priority UDP traffic. SWAN uses feedback information from the network instead of depending on signaling and state information. It automatically configures the rate controller of low priority traffic by measuring MAC delay of ACK frames. Also by measuring the rate of real-time flows that passes through its neighbors, it evaluates the amount of bandwidth that are still available for new real-time connections, thus configuring the admission control. Whenever a mobile node suffers from QoS degradation, it marks every forwarded packet with an Explicit Congestion Notification (ECN) flow. Then the destination of a packet marked with ECN should notify the source of the flow, so that it blocks transmission or adapts it to the new conditions. SWAN provides a simple and effective solution. However, this model does not work well in scenarios where most of the traffic is real time in nature. Even though this model is scalable, it can not provide hard QoS guarantees due to lack of resource reservation at the intermediate nodes. An admitted real-time flow may suffers from periodic violations in its bandwidth requirements. Also it may be dropped or may be made to live with downgraded best-effort service in worst case.

4.3.6 iMAQ

The Integrated Mobile Ad Hoc QoS framework (iMAQ) [35] makes use of a cross layer design of the location-aware routing and middleware layer to support the transmission of multimedia data over a MANET. The framework relies on a location based proactive QoS routing protocol to predict movement of the nodes and network partitioning. Furthermore, it includes an additional middleware for data replication and service lookup on mobile devices attempting to provide the best service for data accessibility to the users. The update protocol floods location and resource information through the network.

4.3.7 ASAP

Xue et al [55] proposed a new QoS framework for MANETs called Adaptive Reservation and Pre-allocation Protocol (ASAP). It uses two-phase reservation mechanism (soft reservation and hard reservation). ASAP is designed to overcome the limitations of INSIGNIA. The framework includes a QoS signaling protocol and flexible allocation and adaptation mechanisms. When a bandwidth request arrives, the soft reservation checks the available bandwidth and reserves the resource for future use. The soft reserved resource can be temporarily used by other traffic (both best-effort and QoS traffic) but can not be reserved by other real-time flows. After the soft reservation, a hard reservation procedure cleans up the soft reservation by forcing out the traffic which temporarily occupies the soft-reserved resources and admits the real-time flow that made the reservation. In case of broken paths, the local repair mechanism in ASAP facilitates stable and continuous QoS provisioning.

5. QoS Routing Protocols

QoS routing has received attention recently for providing QoS in wireless ad hoc networks and some work has been carried out to address this critical issue. In this paper, we investigate the problem of QoS-based routing in mobile ad hoc networks with respect to the following metrics:

- Bandwidth
- End-to-end delay
- Reliability
- Energy efficiency
- Routing Load

However most of the routing protocols discussed below use bandwidth as a QoS metric, since bandwidth is the most critical parameter in most applications due to the scarcity of this resource. There are also some applications in real life which need to guarantee more than one QoS constraint such as guarantee of minimum bandwidth as well as maximum delay. Such type of multi constraint QoS metric protocols have also been covered in this paper. We classify different proposed QoS routing protocols for MANETs in different groups depending on the best effort routing algorithm which they extend or most closely resemble (AODV, DSR, DSDV, TORA) [64]. Moreover, some protocols are also based on new algorithms. Though most of the QoS routing protocols are designed to operate within the network layer, some of the implementation also go below the network layer into the MAC layer.

In the following sections, different QoS routing protocols are presented grouped according to which best effort routing protocol they extend or to which they are most closely related. We also briefly describe approaches for design and implementation of these QoS routing protocols operating either at network layer or network layer as well as MAC layer both along with their merits and demerits.

5.1 Approaches using Extension of DSDV

Under this section, we discuss those QoS routing protocols which are derived from destination sequenced distance vector routing (DSDV) protocol.

Chen et al. [18] addressed the problem of supporting multimedia, multi-hop, mobile communications in a wireless environment using QoS routing. Their approach is cluster based and routing scheme is derived from DSDV [64] (destination sequenced distance vector) which provides QoS information. The main focus of the paper is the QoS routing procedure which can inform the source about bandwidth and quality of service available to any destination in the wireless network. This knowledge enables the establishment of QoS connections within the wireless network and efficient support of real time, multimedia traffic. Limitation of their approach is that it has no support for multi-path routing. Also, as it uses a proactive routing protocol DSDV, a lot of precious bandwidth is wasted in maintaining up to date routing information.

Hsu et al. [19] proposed a DSDV-based routing algorithm to compute the path bandwidth in order to support QoS routing in ad hoc network. The MAC layer in this is CS (Channelized and Slotted) MAC. They presented two rules (Half rule and Floating rule) to divide the overlapped common free slots among channels. Floating rule performs slightly better than the Half rule. The simulation results show the benefits of bandwidth computation and reservation where packet loss rate can be lowered and call dropping rate is controlled. This protocol also addresses the hidden terminal problem.

Lin et al. [22] proposed a bandwidth routing algorithm for multimedia support in a multi hop wireless network which can satisfy minimum bandwidth QoS constraint. This bandwidth routing algorithm includes bandwidth calculation and reservation schemes. This bandwidth calculation and reservation are used over the loop-free DSDV (Destination sequenced Distance vector) routing algorithm. The MAC layer is implemented using TDMA.

Lin et al. [20, 23] proposed a new bandwidth routing scheme which contains bandwidth calculation and reservation for mobile ad hoc networks. It uses CDMA-over-TDMA model. In this protocol, the bandwidth information is embedded in the routing table. By exchanging routing table, the end-to-end bandwidth of the shortest path for a given source-destination pair can be calculated. If enough bandwidth is not there over the shortest path, a call request will be rejected. However, the lack of enough bandwidth over the shortest path does not mean that there does not exist any other bandwidth route in the network. Therefore, this protocol may miss some feasible bandwidth routes as they are not shortest in hop distance. Also CDMA-over-TDMA model is costly for implementation than a protocol using TDMA environment. To support fast rerouting during path failures, the bandwidth routing protocol maintains secondary paths. When the primary path fails, the secondary route is used which acts as primary route and another secondary route is discovered. This protocol also solves the problem of hidden-terminal problem.

5.2 Approaches using Extension of AODV

In this section, we review some of those QoS routing protocols which are derived from ad hoc on demand distance vector (AODV) protocol.

Gerasimov et al. [17] and Renesse et al. [54] proposed an integrated route discovery and bandwidth reservation protocol called QoS-AODV, a protocol that combines on-demand routing with an efficient MAC layer resource reservation mechanism. This protocol is a modified and enhanced version of the ad hoc on-Demand Distance vector (AODV). They have introduced a link and path bandwidth calculation mechanisms and a resource reservation protocol into the original AODV protocol. The focus of the work is on bandwidth reservation within a TDMA framework. Unlike other path finding and route discovery protocols that ignore the impact of the data link layer, QoS-AODV incorporates slot scheduling information to ensure that end-to-end bandwidth is actually reserved. QoS-AODV uses some of the scheduling mechanisms presented in [20]. However approach in [17] is different in that they incorporate QoS path finding based onbandwidth-scheduling mechanism into an already existing ad hoc routing protocol. Moreover, this routing algorithm is fully aware of the bandwidth resource availability and MAC TDMA layer. However race condition is a limitation of this routing protocol.

Perkins et al. [15] and Lakkakorpi [72] proposed a QoS provisioning extension to the Ad hoc On Demand Distance Vector Routing (AODV) protocol [65]. To provide QoS, packet formats (RREQ and RREP) and routing table structure have been modified in order to specify the service requirements which must be met by the nodes forwarding a route request (RREQ) or a route reply (RREP). The following fields are appended to each routing table entry:

- Maximum delay
- Minimum available bandwidth
- List of sources requesting delay guarantees
- List of sources requesting bandwidth guarantees.

The source node initiates a route request (RREQ) with required QoS values (max. end-to-end delay, min. bandwidth and jitter). Each intermediate node subtracts its NODE_TRAVERSAL_TIME (node_t) from the required end-to-end delay. If any node finds that the remaining end-to-end delay is less than the node_t then it drops the RREQ. If, after establishment of such a route, any node along the path detects that the requested QoS parameters can no longer be maintained, that node must originate an ICMP QOS_LOST message back to source node. The advantage of QoS AODV protocol is the simplicity of extension of the AODV protocol that can potentially enable QoS provisioning. But, as no resources are reserved along the path from the source to the destination, this protocol is not suitable for applications requiring hard QoS guarantees. Also as node_t which is a constant value, is only the processing time for the packet, the major part of the delay at a node is contributed by packet queuing and contention at the MAC layer. Hence a packet may experience much more delay than this when the traffic load is high in the network. This protocol is also not tuned to a particular MAC layer. It also does not consider the interference between neighboring links, or between multiple hops of the same flow. Gerasimov et al. [31] presented a comprehensive performance analysis and comparison of two on demand QoS-aware routing protocols (QoS-AODV and QoS-TORA).

Zhu et al. [32] presented an AODV-based QoS routing protocol in TDMA networks. It is designed to function in the network layer. The protocol establishes QoS routes with reserved bandwidth on a per session (flow) basis. It incorporates a distributed algorithm for calculating end-to-end bandwidth on a path efficiently. This bandwidth calculation algorithm is integrated into the AODV protocol in search of routes satisfying the bandwidth requirements. This routing protocol can also restore a route when it breaks due to some topological change. It uses soft-state timers to release slot reservations if the route is not constantly used to send data. The QoS routing protocol builds different QoS routes for individual flows even between the same source and destination. It performs best in smaller networks with low to medium node mobility. Limitation of this protocol is that when multiple QoS routes are being setup, they may interfere with one another resulting in the degradation of the throughput.

Chen et al. [39] proposed a QoS-Aware Routing Protocol that either provides feedback about the available bandwidth to the application (feedback scheme), or admits a flow with the requested bandwidth (admission scheme). Both the feedback scheme and admission scheme require knowledge of the end-to-end bandwidth available along the route from the source to the destination. In this paper only bandwidth has been considered while studying QoS-aware routing for supporting real-time video or audio transmission. Their work focuses on exploring different ways to estimate available bandwidth, incorporating a QoS-aware scheme into the route discovery procedure and providing feedback to the application through a cross-layer design. They use two method for estimating bandwidth, one for hosts to listen to the channel and estimate the available bandwidth based on the ratio of free and busy times ("Listen" bandwidth estimation). The other is for every host to disseminate information about the bandwidth it is currently using in the "Hello" messages, and for a host to estimate its available bandwidth based on the bandwidth consumption indicated in the "Hello" messages from its two-hop neighbors ("Hello" bandwidth estimation). Their protocol improve packet delivery ratio greatly without impacting the overall end-to-end throughput, while also decreasing the packet delay and the energy consumption significantly. Limitation of this protocol is that no predictive way to foresee a route break is incorporated in it, which causes performance degradation due to mobility. Incorporating different transmission ranges among all the hosts and analyzing fairness among the hosts could be taken as a further improvement in this protocol.

5.3 Approaches using Extension of DSR

In this section, we survey those QoS routing protocols which operate on the principle of dynamic source routing (DSR).

Ho et al. [21,49] proposed an On Demand based QoS routing protocol to achieve QoS requirement**.** This paper examines superiority of On Demand QoS Routing over QoS based DSDV [18, 19, 22, 20, 23] in terms of time delay, control overhead and successful rate. DSDV-based QoS routing protocols waste precious bandwidth in flooding routing table periodically when network topology changes. Even though they have full information to every other node, the size of routing table and the amount of table exchanging increases tremendously as the number of mobile nodes and mobility increase. The control messages overhead finally takes up most of the time slots, thus decreasing successful rate and without any quality of service guarantee. Whenever nodes in the route move or the desired time slots are taken up, “QoS without re-route” strategy drops the call directly, while “QoS with reroute” strategy will find another route for this real-time traffic. On the contrary, although on Demand based QoS routing protocol (ODQoS), does not have full information to each other nodes, the size and amount of control packets are small and can be easily handled during control phase of time frame. Another benefit of ODQoS is that it is scalable as the control overhead does not increase with the network size and the node mobility. Papers [21, 37, 24, 25, 42, 48, 49] proposed on demand QoS routing protocol for mobile ad hoc network. Routing protocol proposed by Ho et al [21,49] consists of two phases namely: route construction and route maintenance phases. MAC layer in this case is implemented using TDMA. This protocol is scalable.

Lin et al. [37] and Lin [24, 48] proposed a protocol which focuses on finding a bandwidth route, and the routing optimality is of secondary importance. That is, the bandwidth route obtained from their protocol may not be the shortest one. In Figure 6, Z intends to compute the bandwidth to X. By using their proposed end-to-end bandwidth calculation scheme, if Y can compute the available bandwidth to X, then Z can use this information and the link bandwidth to Y to compute the bandwidth to X. MAC layer is CDMA over TDMA. During the route discovery process, the route request (RREQ) packets (<packet_type, sender_addr, receiver_addr, source_addr, dest_addr, sequence#,route_list, slot_array_list, data, TTL>) are used not only to find paths between the source-destination pair, but also to calculate bandwidth hop-by-hop. If there is no enough bandwidth to satisfy the QoS requirement at any intermediate node, the RREQ packet is to be dropped. Thus, when a RREQ packet arrives at the destination, the route piggybacked on the RREQ packet must satisfy the end-to-end QoS requirement. Also in the route reply process, the route reservation is made hop-by-hop. After calculating the end-to-end bandwidth, data slots are reserved from the destination hop-by-hop backward to the source. In this way, destination node receives more than one path. This multiple connectivity between source and destination pair provides a more robust packet delivery. This protocol is more powerful in resource management than the protocol proposed in [20].

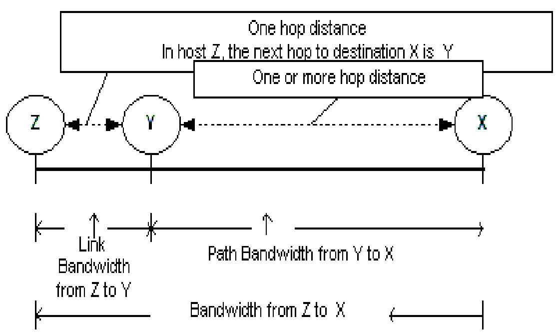

Figure 6. Bandwidth information calculation

Ad Hoc QoS On-Demand Routing Protocol (AQOR)

Xue et al. [42] proposed Ad hoc QoS On-demand routing (AQOR). It is a resource reservation and signaling algorithm and provides end-to-end support in terms of bandwidth and end-to-end delay in an unsynchronized MANET. The route is discovered on-demand by propagating the RREQ and RREP packets between the source and the destination. Their route discovery algorithm is implemented by route exploration from source to destination and route registration in the reverse path. One of the most important thing in this protocol is that it uses an adaptive route recovery model when a QoS violation has been detected. AQOR uses HELLO packets to keep an updated view of the neighborhood. Upon failure of the connection between a pair of nodes, the protocol employs destination-initiated recovery in order to establish a new connection between them. Because of its instant QoS violation detection and recovery mechanisms, AQOR scales well with node mobility. AQOR protocol maintains neighbor information to incorporate interference. The bandwidth calculation and resource reservation model in this protocol showed promising results.

Raju et al. [47] proposed a QoS routing algorithm which accommodates imprecise state information. They applied Fuzzy logic for modeling imprecision. A rule based fuzzy logic model is used to describe imprecise state information. Theyproposed a distributed QoS routing scheme that selects a network path with sufficient resources to satisfy a certain delay requirement low cost path in a dynamic multi-hop mobile environment.

Liao et al. [30] proposed a multi-path, on demand, ticket-distribution QoS routing protocol for finding a route for bandwidth constrained environment. However their multi-path approach does not consider the radio interference problem.

Chen et al. [44] presented a ticket-based protocol for CDMA-over-TDMA for ad hoc networks which allow an intermediate node to extend the route request using multiple links with its neighbors if no single link has enough bandwidth to satisfy the request. It is a multi-path QoS routing protocol for finding a route with bandwidth constraints in a MANET. The basic idea of the on-demand, link-state, multi-path, routing protocol is to reactively collect link-state information from source to destination. The purpose is to dynamically construct a flow network, which is a network topology sketched from source to destination. In this protocol, every mobile node knows the available bandwidth to all its neighbors. When a source needs a QoS route to a given destination, it sends a route request (RREQ) packet to the neighbors who can satisfy the bandwidth constraint. During the propagation of RREQ, each RREQ packet records the link-state information from source to destination. The destination will take as many RREQs it can and perform calculation to find the best paths that satisfy the bandwidth back to the source. After this, it sends route replies (RREPs) back and the resources are reserved on the way back to the source. Link-state algorithm adds protocol overhead. However, it solves the radio interference problem of Liao et al. [30] by using a CDMA-over-TDMA channel model.

TDMA-Based Bandwidth Reservation Protocol

Liao et al. [28] presented a DSR based routing protocol for TDMA-based bandwidth reservation protocol for networks which reserves a QoS path with a certain amount of required bandwidth using a slot reservation mechanism. This paper also addresses the problems of hidden terminal and exposed terminal problems. However, this protocol does not consider several issues, such as racing conditions and parallel reservation problems which could become more significant with increased node mobility, network density and higher traffic loads. These race conditions can reduce the throughput and efficiency as mobility of the nodes increases.

Race Free TDMA-Based Bandwidth Reservation Protocol

Jawhar et al. [29,38,45] extended the work of Liao et al. [28] and presented a race-free TDMA-based bandwidth reservation protocol for QoS routing in mobile ad hoc networks. This protocol remedies the race condition (Figure 7) and parallel reservation problem (Figure 8). Race condition occurs when multiple reservations happen simultaneously at an intermediate node. This would create a conflict when source nodes start using these reserved QoS paths to send data. In figure 7, slot t was reserved for two different paths (path $X \rightarrow Y \rightarrow Z$ and for path $U \rightarrow Y \rightarrow V$). The conflict arises when the packets are transmitted from X to Z and U to V simultaneously, and two data packets from two different paths arrive at node Y. In this case, node Y must decide which data packet it will actually send. The other data packet will be dropped. Now we explain another race condition which arises due to parallel reservation.

Consider Figure 8. In this case, reservation is being done on two parallel paths, $W \rightarrow X \rightarrow Y \rightarrow Z$ and $P \rightarrow Q \rightarrow R \rightarrow S$. Two or more of the intermediate nodes belonging to the two parallel paths are 1-hop neighbors. In this case node X, which belongs to the first path, and node Q, which belongs to the other path are 1-hop neighbors. This is indicated by a dashed line in the figure. The same relationship occurs between nodes Y and R when RREQ1 is propagating from node W to Z, the slots are allocated at the intermediate nodes. However, if the slot allocation information is not maintained by the nodes say node X, but only placed in the RREQ1 message, then no memory of this allocation is keptby the node. This can cause another type of race condition, which is called parallel reservation problem. The protocol proposed in [29,38,45] uses a more conservative strategy. This strategy is implemented using three states for each slot: free, allocated and reserved to better control this process and provide race-free operation. Also it uses wait-before reject at an intermediate node with three conditions to alleviate the multiple reservations at intermediate node problem. In addition, this algorithm provides a solution to the parallel reservation problem in QoS routing, which was not addressed in previous research. Limitation of this protocol is that performance analysis of this protocol has not been done so far through simulation.

Dynamic Range TDMA-Based Bandwidth Reservation Protocol

Jawhar et al. [34] presented a dynamic range bandwidth reservation protocol for wireless networks. It is an on demand and source–based protocol for MANETs operating in TDMA environment. In this protocol, a source node S, desiring to send data, first sends a request message (QREQ) to rserve a QoS path to the desired destination node D. In the reservation message, the source node specifies a dynamic range [b_{min}, b_{max}] of the number of slots needed to transmit the data. The intermediate nodes along the path try to reserve a number of slots, b_{cur}, that is equal to the maximum number of slots that are available within this range ($b_{min} < b_{cur} < b_{max}$). The protocol also permits intermediate nodes to dynamically "downgrade" existing paths that are functioning above their minimum requirements in order to allow the successful reservation of the maximum number of requested paths. When the network traffic load is later decreased, the existing paths are able to be "upgraded" to function with higher bandwidth requirements that are close or equal to the maximum desired level (b_{max}). This allows the network to admit new QoS paths instead of denying such requests by allowing for "graceful degradation" of other paths. Other optimization techniques have also been discussed to increase the efficiency and throughput of the network. This protocol could be extended to include other constraints such as delay, packet loss rate etc.

Delay Sensitive QoS Routing Protocols

Sheu et al. [62] analyzed the relationship between the MAC delay and the neighbor number in mobile ad hoc networks, and provided an estimation method of the MAC delay. Sun et al. [63] analyzed queuing delay by using two dimension finite–state Markov model. They gave the queuing delay distribution Pr (D<t). The average queuing delay is defined to be the value D for which the delay distribution is larger than 90%. Thus, the end-to-end delay of a path can be estimated by adding all the node delays and link delays in the path. Du et al. [61] presented a new on demand QoS routing protocol for delay sensitive real time traffic with end-to-end delay requirement. The goal is to establish delay guaranteed QoS routes in MANETs. The end-to-end delay of a path is the summation of the delay at each node plus the link delay at each link on the path. It includes the protocol processing time and the queuing delay at node i for link (i,j). Link delay is the propagation delay on link (i,j). The propagation delay is very small and almost equal for each hop on the path. Therefore queuing delay and MAC delay are two main factors that accumulated the node's delay. The QoS routing protocol takes advantage of the better transmission capability of backbone (B-node) nodes. Most links along the QoS route are between B-nodes, which have less node delay and large transmission range. Less node delay increases the chance to meet the QoS delay requirement and large transmission range reduces the number of hops in the route, and also reduces the end-to-end delay.

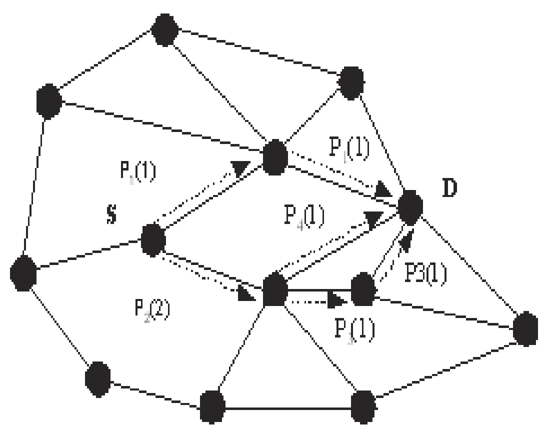

Figure 9. Ticket based path discovery

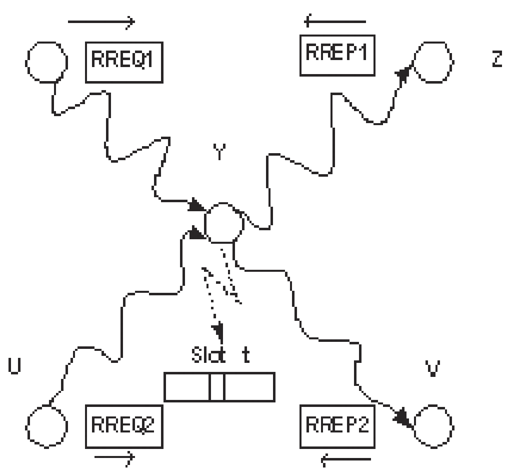

Figure 7. Race condition of two QoS paths passing through a common intermediate node

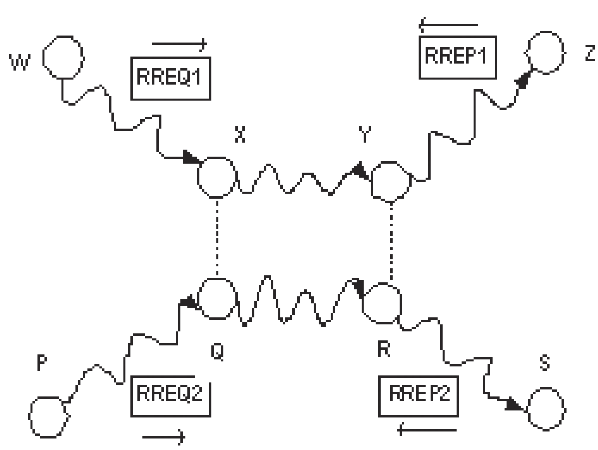

Figure 8. Parallel reservation problem at nodes X and Q as well as at nodes Y and R

5.4 Multipath QoS Routing protocols

Multipath routing allows the establishment of multiple paths between a single source and a single destination node. In the following, we discuss the role of multipath routing to provide quality of service, more specifically to reduce end-to-end delay, to avoid or alleviate the congestion in the network, and to improve the end-to-end throughput, etc.

5.4.1 Ticket-based QoS Routing Protocol

Chen et al. [14] proposed a ticket-based multi-path distributed QoS routing scheme that selects a network path with sufficient resources to satisfy a certain delay or bandwidth requirement. This protocol maintains the end-to-end state information at every node for every possible destination. This information is updated periodically by a distance vector protocol like DSDV. It considers two kinds of routing criteria: the delay-constrained least-cost routing and the bandwidth-constrained least cost routing. Tickets are used to limit the spreading of route request (RREQ) messages. Actual bandwidth reservation takes place at each hop, and along all paths, from a source to the destination. Multiple paths are searched in parallel to find the most qualified one without flooding. Figure 9 illustrates an example of a route discovery with ticket based probing. Source node S tries to establish a QoS constrained connection to a given destination D. It issues two probes, P_1 carrying one ticket while P_2 carrying two tickets. P_1 is propagated directly on the most promising path towards D without any further split. P_2 seemed more promising to S and thus has been equipped with two tickets. An intermediate node split P_2 into two probes P_3 and P_4, each carrying just one ticket. When all three probes reach to destination D, it evaluates the probes and issues a response to S along the reverse route.

The protocol allows for multiple levels of redundancy for fault tolerance in order to protect certain flows against unpredictable topology changes. Depending on the importance of a flow, reservations can be done on multiple paths at once and packets may be even copied and transmitted along several of these paths simultaneously. The bandwidth and delay information are also assumed available. This algorithm tries to limit flooding by issuing limited tickets. This protocol does not consider the interference between neighboring links, or between multiple hops of the same flow. Also the work in this assumed that the bandwidth of a link can be determined independently of its neighboring links. This strong assumption may be realized by a costly multi-antennas model such that a host can send/receive using different antenna independently and simultaneously. Moreover this protocol may experience a high failure rate when the bandwidth demand is large. Advantage of this protocol is that due to distributed path calculation, this protocol is scalable. However, the path finding procedure is not designed to take advantage of QoS information available at the MAC layer. This in turn can lead to underutilization of network capacity.

5.4.2 Multi-Path QoS Routing Supporting DiffServ Protocol

Li et al. [58] proposed a protocol called NDMR which modifies and extends AODV to enable path accumulation feature of DSR in route request/reply packets and discover multiple node-disjoint routing paths with a low routing overhead. Although NDMR provides nod-disjoint multi-path routing with low route overhead in MANETs, but it is only a best effort routing approach which is not sufficient to support QoS. DiffServ is an approach for a more scalable way to achieve QoS in IP network. It could be a potential QoS model in MANETS because it acts on aggregated flows and minimizes the need for signaling. However, one of the biggest drawbacks of DiffServ comes from the fact that the QoS provisioning happens separate from the routing process. MQRD [57] combines the advantages of NDMR and DiffServ and makes it suitable for the environment of MANETs with QoS support.

5.4.3 Spiral Multi-Path QoS Routing Protocol

Chen et al [67] proposed a SMPQ (Spiral Multi-Path QoS) to identify a robust path, namely spiral-multi-path, from source to destination host to satisfy certain bandwidth requirements. Chen et al [60] presented a robust spiral-path routing protocol.However, the result was not the QoS-awareness routing protocol. To support the QoS guarantees, Chen et al. in [67] proposed a scheme, to combine the spiral-path and multi-path routing result to develop a new QoS routing protocol, which inherits the robust path capability from the spiral-path schemes [60] and the better success rate from the multi-path scheme [30]. SMPQ protocol strengthens the route-robustness and route stability properties also it increases the success rate of finding QoS routes.

5.4.4 Disjoint Multi-Path QoS Routing Protocol

Li et al. [68] proposed a disjoint multi-path QoS routing protocol for ad hoc networks. This scheme can find multiple disjoint paths whose aggregate bandwidth can satisfy the bandwidth requirement of a call. Even though multiple paths were provided in [67] and some other similar multi-path routing schemes, but they need not be disjoint and intermediate links are shared by multiple paths. In [68] compared with non-disjoint multi-path methods, this approach can reduce the system congestion and make better use of network resources. Unlike some other protocols that consider resource reservation during the route discovery, here it firstly collects link bandwidth information from source to destination in order to find multiple disjoint paths; secondly, choose proper paths at the destination node according to the bandwidth and hop-count of each path and lastly reserves necessary bandwidth resource over each selected path by sending route-reply (RREP) packets. In their paper, bandwidth is the primary metric and the hop-count is the secondary metric in selecting multiple disjoint paths. Therefore their method is called Largest Bandwidth-Hop-Bandwidth First method.

5.4.5 Interfering –Aware Multi Path Routing Protocol

Wang et al. [56,59] proposed an Interfering-aware Multi-path Routing Protocol (IMRP) with QoS constraint for multimedia and real-time applications in ad hoc wireless network. When the multiple paths are close together, transmissions of different paths may interfere with each other, causing degradation in performance. IMRP is a source initialized, on-demand, and multiple paths routing protocol. With available bandwidth pre-evaluation and interfering susceptibility, IMRP will reduce the call dropping rate and improve the QoS stability. A MAC protocol with power control scheme decreases the interfering ratio between routing paths. But, the bandwidth evaluation will be more difficult due to the dynamic transmitting power. The MAC with power control scheme must evaluate its available bandwidth according to its maximum transmitting power.

5.4.6 QoS Routing Protocol using Reliability as QoS-Metric

Leung et al. [66] proposed a QoS-aware multi-path dynamic source routing protocol (MP-DSR). It is a fully distributed QoS protocol, which creates and selects routes based on a newly defined QoS metric, end-to-end reliability. This protocol identifies a number of disjoint paths from a source to destination. These paths, taken together are expected to satisfy a given end-to-end reliability constraint. Given a reliability requirement P_u, this algorithm determines the number of disjoint paths it needs to discover and the reliability constraint that each disjoint path must satisfy in order to provide an overall reliability of P_u. When an application wants to use MP-DSR for route discovery, it supplies a minimum end-to-end requirement, based on which the protocol determines the number of paths needed (m_0) and the lowest path reliability (π_{lower}) requirement that each path needs to provide. The source node then sends out m_0 RREQ packets, each of which contains information such as Π_{lower}, the path traversed, the corresponding path reliability etc. When a node receives the RREQ message, it checks whether the message meets the path reliability requirement. If so, the corresponding node will update the RREQ message (including itself in the traversed path and corresponding reliability) and forwards multiple copies of this message. The number of copies is based on the number of neighbors that can receive this RREQ without failing the path reliability, and also bounded by m_0 to restrict the message forwarding in the network. When the destination receives the RREQ messages, it then selects node-disjoint paths and RREP messages back to source along these disjoint paths. In response to this, the source node begins sending data via routes from which it receives the route replies. In comparison to protocol proposed in [14], MP-DSR considers the dynamic nature of network topology as well as the importance to offer continuous network connection in certain mission critical applications. Also, MP-DSR differs in the way of searching multiple paths; the route discovery in this protocol relies on local link availability information at each intermediate node to perform the route request (RREQ) message forwarding, without resorting to any global information as was used in [14].

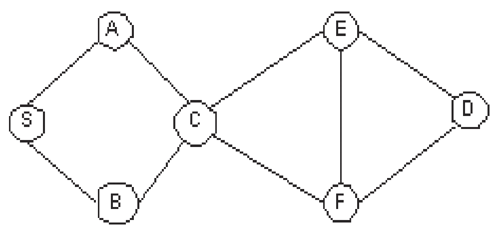

Figure 10. A Network Topology in which MP-DSR does not compute link disjoint paths.

However this protocol can not compute link disjoint paths in many cases because the intermediate nodes drop every duplicate RREQ that may comprise another link disjoint path. Figure 10 shows a typical case in which MP-DSR can not compute link disjoint paths as node C discards one of the RREQs from node A and node B because it is a duplicate copy.

5.4.7 Fault Tolerant Routing Protocol

Agarwal et al. [70] proposed a fault-tolerant routing protocol for MANETs using segmented backup paths. They identified an optimal primary path which satisfies the required QoS constraints along with a set of alternate paths that may be used in case a link/node on the primary path fails.

The alternate paths are also required to satisfy the same set of QoS constraints as is the case with primary path. Their approach is different in the sense that the traffic be rerouted along a sub-path that by-passes a segment or a portion of the primary path that contains the failed link/node. The identification of the segments and their size is not fixed a priori but will be determined based on availability of alternate paths so that QoS constraints are met.

5.5 Energy Efficient Routing Protocol

Energy efficient routing has been one of the subjects of intensive study in recent years. The goal of energy efficient routing protocols is to find the best path such that total energy consumption by the network could be minimized. Another objective of energy aware routing protocol is to maximize the system lifetime, which is defined as the duration when the system starts to work till any node runs out of energy.

Zhang et al. [71] proposed a protocol CEQRP (Cost-Efficient QoS Routing Protocol) which provides QoS guarantee and is aimed at extending the battery's life time at each host by selecting the hosts with a long residual battery lifetime to forward packets. Many routing algorithms with QoS guarantee, such as [15,20], are proposed, but these protocols do not consider efficient use of host energy. In CEQRP, every host has a cost which reflects its remaining lifetime to forward packets. The less a host remains its electric energy, the more value its cost will be. The host with smaller cost value is requested to forward packets for a virtual circuit path if both hosts can satisfy the demands of routing and QoS. This can extend the battery's worst case lifetime at each host. Thus the life time of the network can be extended.

5.6 Predictive-Location Based QoS Routing Protocol

Shah et al. [9,10] proposed a predictive location-based QoS routing protocol which is based on prediction of locations ofnodes in Ad hoc mobile wireless networks. Location-based routing schemes have been previously used in ad hoc routing in protocols such as LAR [11] and DREAM [12]. Both LAR and DREAM use a very weak prediction mechanism. These protocols do not take the direction of motion of the destination into account when attempting to predict the location at a future instant. In Shah et al paper, instead of disseminating the state of each link network wide, each node broadcasts its node status including its current position, velocity, moving direction and available resources on each of its outgoing links across the network periodically or upon a significant change. With such information, at any instant each node can locally predict an instant view of the entire network. To accommodate a QoS request, the source locally computes a QoS satisfied route (if available) and route data packets along the calculated path. Moreover, the source can predict route break and in advance compute a new route before the old route breaks by using the global state it stores. This routing protocol is suitable for providing soft QoS in small or medium sized networks wherein mobile hosts are equipped with Global Positioning System and their moving behavior is predictable. Even soft QoS guarantees may be broken in cases when network load is high. Since the location prediction mechanism inherently depends on the delay prediction mechanism, the inaccuracy in delay prediction adds to the inaccuracy of the location prediction. The end-to-end delay for a packet depends on several factors such as the size of the packet, current traffic load in the network, scheduling policy, processing capability of intermediate nodes, and capacity of links. As the delay prediction mechanism does not take in to consideration some of the above factors, the prediction made by the location prediction mechanism may not be accurate, resulting in QoS violations for the real-time traffic.

5.7 A Hybrid QoS Routing Protocol (CEDAR)

Sinha et al. [13] proposed a core-extraction distributed ad hoc routing (CEDAR) algorithm. It establishes a core of network (Figure 11) dynamically and then incrementally propagates the link state of stable high bandwidth links to the nodes of the core. Route computation is on demand and is performed by core nodes using only local state. It includes three key components: core extraction, link state propagation, and route computation. A core node performs route computations on behalf of other nodes present in its domain. When a node wants to communicate to a destination, it contacts its dominator node in the core to find a route to the destination, which meets the QoS requirement. Nodes in the core use core broadcast to exchange network topology information with other nodes in the core. This algorithm is designed to select routes with sufficient bandwidth resources. In Figure 12 black node represents core node. Solid line denotes links in the ad hoc network whereas dotted lines denote virtual links in the core graph.

In this paper the load factor at core nodes and how it can affect the network performance are not addressed. Also due to the dynamic nature of an ad hoc network, the core may be broken at transient time periods during which the routing can not be effectively done. Furthermore, searching for a

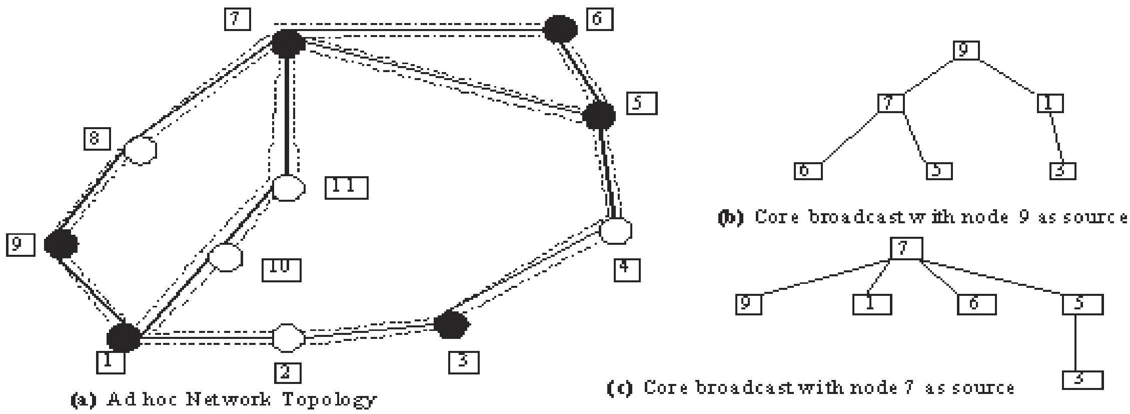

Figure 11. Example of a Core Broadcast

QoS constrained path is directed by the core. The tree structure of the core may not lead to discovery of the shortest feasible path that often takes a shortcut between tree branches. In the CEDAR routing protocol, it is assumed that the available bandwidth is known. The available bandwidth is disseminated among the cores. In this way, the overhead used to propagate the link state information can be minimized. However, if the core is moving out of the selected route, rerouting is very costly. The advantage of this protocol is that it tries to minimize over-head in setting up the route. This protocol can be used as a QoS routing algorithm for small to medium size mobile ad hoc network consisting tens to hundreds of nodes.

5.8 Load-Aware Routing Protocols

Routing with load balancing in wired networks has been exploited in different approaches [40,41,43]. There is a tendency in ad hoc networks routing protocols to use a few centrally located nodes in a large number of routes. This causes congestion at the medium access control (MAC) level, which in turn may lead to high packet delays and bottlenecks when a large number of data packets pass by such few nodes. As over utilized nodes would suffer from high battery power consumption, the survival time of the whole network may be shortened. As a result, it is necessary to take into account the route load and congestion conditions of nodes in the route selection process to balance and distribute the traffic load to the network nodes. In fact, a major drawback of most existing ad hoc routing protocols is that they do not have provisions of conveying the load or quality of a path during route setup. Hence they often fail to balance the load on the different routes. In the following, we review two different proposed routing protocols that use route load as the primary QoS metric.

5.8.1 Dynamic Load-Aware Routing Protocol

In DLAR (Dynamic Load–Aware Routing) protocol [77], the load metric of a node is defined as the number of packets buffered in the node interface queue, and the load metric of a route is the summation of the load metrics of the nodes on that route. However, this technique does not optimally reflect the actual load since buffered packets may vary in size. In the route construction phase, it selects the least-loaded routes according to the load information collected by the RREQ packets, and periodically monitors the congestion status of active sessions and dynamically reconfigures the routes that are being congested during the route maintenance.

Consider Figure 12. In this network, DLAR protocol will add the routing load of each intermediate node along each path and select the least loaded route (i.e., route k: $(S \rightarrow X \rightarrow N \rightarrow O \rightarrow Z \rightarrow D)$ as against to min-hop route j: $(S \rightarrow X \rightarrow Y \rightarrow Z \rightarrow D)$). In DLAR, the destination waits for an appropriate amount of time to learn all possible routes. Then, it sends a route reply choosing the least loaded route. Hence, the source may have to wait for a considerable amount of time before it is able to transmit data. Intermediate nodes also periodically attach their load information with data packets. On detecting congestion, the destination broadcasts a route request packet towards the source. Moreover, the load measurements do not consider the channel contention from neighbor nodes in a wireless network.

5.8.2 Contention Sensitive Load-Aware Routing Protocol

In [76], Li et al. proposed a Contention Sensitive Load Aware Routing Protocol (CSLAR) that utilizes the contention information collected from the 802.11 Distributed Coordination Function (DCF). With this information, the

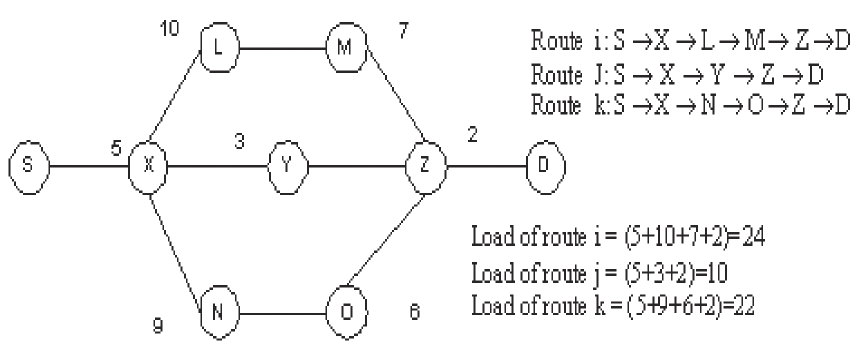

Figure 12. An Ad hoc Network with routing load

channel's contention situation and the neighbor's traffic load can be estimated and considered for making routing decisions. Route selection for mobile node is based on three metrics in CSLAR: contention information from MAC layer, number of packets in its queue and number of hops along the route. This represents a typical cross layer approach, in which every node collects and processes the contention information from MAC layer periodically and passes this parameter to the routing agent during the route discovery process. Based on the NAV (Network Allocation Vector) entry, queue length and number of hops, the over all load (route_load) at a particular node is calculated as per the following equation (1).

$$\text{route\_load} = a \times A_{NAV} + b \times A_{qlen} + c \times N_{hop} \quad (1)$$

where A_{NAV} implies the average busy portion of each second, A_{qlen} implies average queue length, N_{hop} implies the number

A_{qlen} can be obtained from equation (2) and (3)

respectively as mentioned below.

$$A_{NAV} = \alpha \times C_{NAV} + (1-\alpha) \times A_{NAV} \quad (2)$$

$$A_{qlen} = \beta \times C_{qlen} + (1-\beta) \times A_{qlen} \quad (3)$$

Where C_{NAV} refers the busy portion of the current second, α and β are constant in range [0, 1].

6. Summary of QoS Routing Protocols

Various routing protocols discussed above are summarized presented in Table 1. The table contains the following columns. In the first column, routing protocol is listed. Then, "Network Layer" parameter indicates the networking layer within which the protocol is designed to operate. The "Communication Mode" parameter indicates the communication network assumed such as TDMA, CDMA-over-TDMA, and so on. The "Best Effort Routing" parameter indicates the best effort routing protocol that is extended by or is most closely related to the corresponding QoS protocol. The "Proactive/Reactive" parameter indicates whether this QoS routing protocol is reactive (on-demand) or proactive (table driven). Then the "Comments" field contains additional information about the QoS routing protocol.

7.Conclusions and Future Research Directions

Quality of Service Routing is at present an active research area, since most emerging network services require specialized quality of service (QoS) functionalities that can not be provided by the presently available QoS-unaware routing protocols. This technology brings great opportunities together with severe challenges. Providing QoS guarantees in mobile ad hoc networks enable time critical control applications as well as high quality streaming multimedia to run on such networks. QoS routing provides better QoS guarantees to applications and improves the network resource utilization. As it has become an active research topic, researchers are participating in a growing number and numerous works have been reported. In most of the cases, legacy protocols from fixed networks are not adequate for this type of networks, as the radio environment may be hostile and often unstable, introducing new performance issues. In this paper we discussed the major challenges ahead to QoS routing in ad hoc networks. Since QoS provisioning is an inter-layer issue, we identified different QoS frameworks designed exclusively for mobile ad hoc networks and commented on their performance. We reported work in this

QoS Routing	Network Layer	Communication Mode	Best Effort Routing	Reactive/ Proactive	Comments
Chen et al. [18]	Net./MAC	Cluster TDMA	DSDV	Proactive	Computes minimum bandwidth and maximum delay path.
Hsu et al. [19]	Net./ MAC	CS-MAC	DSDV	Proactive	Computes Bandwidth constrained path.
Lin [22]	Net./ MAC	CDMA over TDMA	DSDV	Proactive	Bandwidth routing algorithm for multimedia support.
Lin et al. [20,23]	Net./ MAC	CDMA over TDMA	DSDV	Proactive	Bandwidth routing algorithm with efficient call admission control.
Gerasimov et al. [17] and Re-nesse et al. [54]	Net/MAC	TDMA	AODV	Reactive	Bandwidth reservation protocol (QoS-AODV).
Perkins et al. [15], Lakkakorpi[72]	Net.	No specific MAC layer	AODV	Reactive	Route satisfying bandwidth, end-to-end delay and jitter.
Zhu et al. [32]	Net/MAC	TDMA	AODV	Reactive	Path bandwidth calculation integrated with AODV
Chen et al. [39]	Net/MAC	IEEE 802.11	AODV	Reactive	Approximate bandwidth estimation using two different methods.
Ho et al. [21,49]	Net./ MAC	TDMA	DSR	Reactive	Bandwidth calculation and reservation with minimum time delay.
Lin et al. [37], Lin [24,48]	Net./ MAC	CDMA over TDMA	DSR	Reactive	Bandwidth calculation and reservation algorithm through Route request packet. Routing optimality is of secondary concern.
Xue et al. [42]	Net./ MAC	IEEE 802.11 DCF	DSR	Reactive	Provides on demand QoS in terms of bandwidth and end- to end delay (AQOR).

Table 1. QoS Routing Algorithm Classification

Table 1 (contd.)

QoS Routing	Network Layer	Communication Mode	Best Effort Routing	Reactive/ Proactive	Comments
Raju et al. [47]	Net/MAC	Suitable MAC protocol which resolves media contention	Hop by Hop route selection	Reactive	Delay constrained path with least cost routing. Fuzzy logic technique to model imprecise state information.
Liao et al. [30]	Net./MAC	CDMA over TDMA model	DSR	Reactive	Ticket based Multi-path QoS routing for bandwidth.
Chen et al. [44]	Net/MAC	CDMA-over-TDMA	DSR	Reactive	End-to-end path bandwidth calculation of a multi-path routing when bandwidth is limited.
Liao et al. [28]	Net/MAC	TDMA	DSR	Reactive	TDMA-based bandwidth reservation protocol.
Jawhar et al. [29,38,45]	Net/MAC	TDMA	DSR	Reactive	Addresses the race condition issue of bandwidth reservation protocol.
Jawhar et al. [34]	Net/MAC	TDMA	DSR	Reactive	A dynamic range bandwidth reservation protocol for wireless networks.
Du et al. [61]	Net/MAC	IEEE 802.11	DSR	Reactive	QoS routing protocol for delay sensi tive traffic (algorithm to calculate the min. end-to-end delay for heterogeneous n/w).
Chen et al. [14]	Net.	---	DSR and DSDV	Proactive	Ticket-based QoS routing protocol (bandwidth/delay constrained) with imprecise state.
Li et al. [57]	Net.	---	AODV	Reactive	MQRD: A node-disjoint multi-path QoS Routing of supporting DiffServ.
Chen et al [67]	Net/MAC	CDMA-over- DSR TDMA		Reactive	SMPQ: identify a robust QoS path structure, namely a spiral-multi-path to satisfy Bandwidth.
Li et al. [68]	Net/MAC	CDMA-over-TDMA	DSR	Reactive	Algorithms to find multiple disjoint paths.
Wang et al. [56,59]	Net/MAC	IEEE 802.11	DSR	Reactive	Interfering-aware Multi-path Routing Protocol (IMRP).
Leung et al. [66]	Net/MAC	IEEE 802.11	DSR	Reactive	(MP-DSR) Multi-path routing to improve end- to-end reliability.
Agarwal et al [70]	Net/MAC	IEEE 802.11	DSR	Reactive	A fault-tolerant routing protocol using segmented backup paths.
Zhang et al.] [71	Net./MAC	FDMA over TDMA	DSR	Reactive	CEQRP: a protocol aimed at extending the battery's life time
Shah et al. [9,10]	Net.	---	Source routing	Proactive	A Location-delay based QoS routing.
Sinha et al. [13]	Net.	---	Restricted flooding with localized source routing	Hybrid	CEDAR: provides route computation algorithm with requested bandwidth
Lee et al. [77]	Net/MAC	IEEE 802.11 DCF	DSR	Reactive	Number of packets buffered in the node interface queue as the primary route selection metric
Li et al. [76]	Net/MAC	IEEE 802.11 DCF	DSR	Reactive	Uses three metrics (contention delay, No. of packets in its interface queue, and number of hops) for route selection.

Table 1. QoS Routing Algorithm Classification

area from its inception. We also made a classification of the existing QoS routing protocol approaches according to different criteria. These criteria include extension to the best routing protocol, the OSI layer, and communication model used. Various proposed QoS routing protocols use either a single or multiple QoS metric(s) among bandwidth, end-to-end delay, delay jitter, reliability and load in route selection and also presented on going research efforts. Both single and multipath solutions have been discussed. We critically examined strengths and weaknesses of different approaches used in these protocols.

As wireless networks and devices continue to proliferate and penetrate all aspects of communications in the twenty-first century, providing support for multimedia and real time applications become an important function of the underlying communication protocols. This is done by requiring such protocols to provide QoS guarantees that satisfy the strict constraints imposed by these applications. Given many intriguing future applications, there are still some critical challenges and open problems to be solved in order to provide QoS routing in mobile ad hoc networks. Following are some of the main research challenges in quality of service route provisioning in this network:

- Traffic differentiation and prioritization
- Prototype cross-layer approach to enable multi-hop routing.
- Development of algorithm and metrics that damp oscillating effects of wireless environment.
- Trade-off between QoS algorithm complexity and rapid changing conditions (channel instability and user mobility)
- Interoperation with Internet
- Multiple routes for more reliability
- Location management
- Energy conservation
- Scalability as well as robustness
- Security

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